FINAL REPORT

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NUMERICAL COMPUTATION OF THE CHEMICALLY REACTING FLOW AROUND THE NATIONAL AERO-SPACE PLANE

by

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SUMMARY

This final report summarizes the research accomplished under NASA Grant NAG 2-776 during the entire funded period which extended from February 1, 1992 to January 31, 1999. The total funding amounted to $172,220. The Technical Officers for this grant were Dr. Thomas A. Edwards and Dr. Scott L. Lawrence of NASA Ames Research Center.

INTRODUCTION

The research performed during the grant period can be divided into the following major areas:

1. Computation of chemically reacting scramjet flowfields.
2. Application of a two-equation turbulence model to supersonic combustion flowfields.
3. Computation of the integrated aerodynamic and propulsive flowfields of a generic hypersonic space plane.
4. Computation of hypersonic flows with finite-catalytic walls.
5. Development of an upwind PNS code for thermo-chemical nonequilibrium flows.

These major areas of research are briefly discussed in the next section.

DESCRIPTION OF PERFORMED RESEARCH

1. Computation of chemically reacting scramjet flowfields

A new upwind, parabolized Navier-Stokes (PNS) code was developed to compute the three-dimensional chemically reacting flow in scramjet (supersonic combustion ramjet) engines. The code is a modification of the three-dimensional upwind PNS (UPS) airflow code which was extended in the present study to permit internal flow calculations with hydrogen-air chemistry. With these additions, the new code has the capability of computing both aerodynamic and propulsive flowfields. The algorithm solves the PNS equations using a finite-volume, upwind TVD method based on Roe's approximate Riemann solver that has been modified to account for nonequilibrium effects. The fluid medium is assumed to be a chemically reacting mixture of thermally perfect (but calorically imperfect) gases in thermal equilibrium. The chemistry model contains eleven reactions and nine species and is based on the NASP hydrogen-air model. The new code was applied to two test cases. The first case consisted of the Burrows-Kurkov supersonic combustion experiment in which hydrogen was injected tangentially at sonic speed through a slot in the floor of a test section with a M_∞=2.44 vitiated airstream. In the second test case, the code was used to compute a generic 3-D scramjet (M_∞= 7.0) flowfield. The computed results compared favorably with the available experimental data. Details of this work are presented in Refs. 1-2.

1. **<u>Application of a two-equation turbulence model to supersonic combustion flowfields</u>**

A two-equation ($k - \varepsilon$) turbulence model was incorporated into the UPS (upwind, parabolized Navier-Stokes) code. The turbulence transport equations are solved in an uncoupled manner from the fluids equations. The code has the capability of computing chemically reacting flowfields involving air or hydrogen-air chemistry. The flows around hypersonic vehicles involve turbulent mixing and chemical reactions. With the addition of a two-equation turbulence model, the code can now provide more accurate simulations of these complex flowfields. Four test cases involving turbulent flows were computed to validate the new code. The first two were 2-D perfect gas computations and included a supersonic free-shear layer and a supersonic wall boundary layer. The other two involved finite-rate, hydrogen-air combustion and included the Burrows-Kurkov supersonic combustion experiment and a 2-D supersonic, combusting, free-shear layer. The computed results were in good agreement with the available numerical and analytical solutions. Details of this work are given in Ref. 3.

3. **<u>Computation of the integrated aerodynamic and propulsive flowfields of a generic hypersonic space plane</u>**

In this study, the three-dimensional, tip-to-tail, numerical calculations of the integrated aerodynamic and propulsive flowfields of a generic hypersonic space plane were computed. The Test Technology Demonstrator (TTD) geometry was used to represent the generic hypersonic space plane. The UPS (upwind, parabolized Navier-Stokes) code was used to perform the turbulent, chemically reacting nonequilibrium flow calculations. The UPS code uses a finite-volume, upwind, TVD method based on Roe's approximate Riemann solver. The aim of this work was to bring together all the various capabilities added to the UPS code during this grant, to demonstrate its ability to perform complex flowfield computations, and to study the flow structure around such a configuration. Two test cases, power-off and power-on, were computed. The freestream conditions correspond to an altitude of 100,000 feet (30.5 km) and a Mach number of 10 (a shock-on-lip condition). For the power-on case, a stoichiometric mixture of H_2-air was injected at the throat of the scramjet engine to simulate the combustion conditions. Both tip-to-tail cases were successfully computed in this study. Details of this work are presented in Refs. 4-6.

4. <u>Computation of hypersonic flows with finite-catalytic walls</u>

A computational study was performed to explore the effects of finite-catalytic walls on hypersonic flows. Boundary conditions for noncatalytic, fully-catalytic and finite-catalytic walls were incorporated into the upwind parabolized Navier-Stokes (UPS) code. The code was used to compute the M_∞= 25 laminar flow of chemically reacting air over sharp cones at zero and ten degrees angle of attack at an altitude of 61 km (200,000 ft.). Additional calculations were performed for the $M_\infty = 22$ laminar flow over a sharp cone at zero degrees angle of attack at an altitude of 30.5 km (100,000 ft.). Computations were performed for non-catalytic, fully-catalytic, and finite-catalytic cases and the results were compared with previous results wherever possible. Details of this work are given in Refs. 7-9.

5. <u>Development of an upwind PNS code for thermo-chemical nonequilibrium flows</u>

A new parabolized Navier-Stokes (PNS) code was developed to compute three-dimensional flows in thermo-chemical nonequilibrium. The code is an extension of the 3-D upwind PNS (UPS) code which was previously modified to compute chemically reacting flows in thermal equilibrium. The vibrational and electronic nonequilibrium effects were incorporated via a loosely-coupled approach similar to that used for the chemistry. The new code is believed to be the first PNS code which can be used to compute flows in chemical, vibrational, and electronic equilibrium or nonequilibrium. Test calculations were performed for the inviscid flow through expanding hypersonic nozzles. Comparisons were made with numerical calculations and with data from the AEDC nozzle experiment of MacDermott and coworkers. Details of this work are presented in Refs. 10-12.

CONCLUDING REMARKS

The research performed during this grant is described by the 12 documents listed in the next section. This documentation consists of:

4 Journal articles

6 Technical papers presented and preprinted

1 Ph.D. dissertation

1 M.S. thesis

In addition, the present grant supported the following two students as Research Assistants at Iowa State University:

Ganesh Wadawadigi

James H. Miller

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